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Site Comparison for Optical Visibility Statistics in Southern California

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Negotiations are under way to locate an atmospheric visibility monitoring (AVM) observatory at Mount Lemmon, just north of Tucson, Arizona. Two more observatories will be located in the southwestern U.S. The observatories are being employed to improve a weather model for deep-space-to-ground optical communications. This article explains the factors considered in choosing a location and recommends Table Mountain Observatory as the location for another AVM facility.

I. Introduction

Ground-based receivers of optical communications signals from planetary spacecraft must contend with the adverse effects of the Earth's atmosphere. Spatially diverse receivers will improve link performance by providing at least one site with favorable atmospheric conditions.

The atmospheric visibility monitoring (AVM) project is designed to create an improved weather model for cloud-cover statistics over the southwestern United States. An improved model will help predict the performance of ground-based optical receivers projected for construction. A preliminary model already predicts that it is possible to have clear skies at at least one of three sites 95 percent of the time if the sites are properly distributed throughout the region [1]. In order to determine a more exact weather model, the observatories are being located in areas with a low correlation of cloudy skies, and where facilities already exist to supply roads, power and telephone lines. Several of the candidate sites are already locations of astronomical observatories.

Southern California is known to have favorable weather patterns that differ from those in Arizona and states farther east. This article describes the characteristics of, and recommendations for, a California site selection. Sites considered were Goldstone, Table Mountain Observatory (TMO), Mount Wilson, and Mount Laguna. Their locations are shown in Figure 1.

II. Site Characteristics

Five major site factors were considered, and each given a weighting relative to its importance to AVM. The factors are listed in Table 1. Candidate sites were then rated on a 1-10 scale for each factor. The ratings were in turn weighted and summed to give an overall rating for the site [2].

A. Probability of Clear Skies

Two factors are being considered within this characteristic. First, a site should exhibit a high annual percentage

of clear skies. Second, it should exhibit a low correlation of cloudy skies with the Mount Lemmon site. Annual percentage of clear skies can be determined from ground and satellite data that have been compiled over several years by organizations such as the National Weather Service, the National Climatic Data Center, and the Solar Energy Research Institute. These sources have produced the information in Table 2.

The data in the following paragraphs were compiled by Don Wylie of the University of Wisconsin from three years of Geostationary Operational Environmental Satellite/Visible and Infrared Spin Scan Radiometer Atmospheric Sounder (GOES/VAS) data.¹ The resolution of his data is limited to a 2-deg $\times$ 2-deg box; consequently, TMO and Mount Wilson fall within the same box. The data are for January and July only; however, they tend to give a sufficient indication of what summer and winter conditions are like.

In January, if Mount Lemmon was cloudy, Goldstone was clear 59 percent of the time, TMO and Mount Wilson were clear 52 percent of the time, and Mount Laguna was clear 23 percent of the time. If Goldstone was cloudy, Mount Lemmon was clear 54 percent of the time. If TMO or Mount Wilson was cloudy, Mount Lemmon was clear 63 percent of the time. If Mount Laguna was cloudy, Mount Lemmon was clear 44 percent of the time.

In July, if Mount Lemmon was cloudy, Goldstone was clear 87 percent of the time, TMO and Mount Wilson were clear 84 percent of the time, and Mount Laguna was clear 67 percent of the time. If Goldstone was cloudy, Mount Lemmon was clear 50 percent of the time. If TMO or Mount Wilson was cloudy, Mount Lemmon was clear 50 percent of the time. If Mount Laguna was cloudy, Mount Lemmon was clear 21 percent of the time.

These data indicate that Goldstone, TMO, and Mount Wilson exhibit a much lower correlation of cloudy skies with Mount Lemmon than Mount Laguna does. Other data from Wylie indicating the probability of clear skies, cirrus clouds, and opaque clouds for these sites in January and July are shown in Table 3. These data show that Goldstone has a greater probability of clear skies than any of the other sites. In fact, the number of clear days at Goldstone is comparable to the number of clear days at Mauna Kea, Hawaii, a site well known for its clear skies [5]. Mount Laguna has a higher probability of clear skies than TMO and Mount Wilson; however, the correlation

data show that their cloudiness is more correlated with cloudiness at Mount Lemmon.

Based on this information, the following ratings were given for probability of clear skies: Goldstone: 10, TMO: 9, Mount Wilson: 9, and Mount Laguna: 6.

B. Low Particulate Scattering

Particulate scattering arises from particles in the atmosphere. Scattering will attenuate light transmission and increase daytime sky radiance. Sites at higher elevations tend to exhibit less scattering because the atmosphere is thinner at higher altitudes and there is a shorter path from the ground to space. Large measures of precipitable water vapor (PWV) are an indication of more scattering and higher atmospheric extinction. Measurements of PWV are available from sites involved in infrared astronomy. Sites with vegetation tend to have less dust blown up by winds. Smog, fog, and haze also contribute to higher particulate scattering. LOWTRAN7, a low-resolution propagation model for calculating atmospheric transmittance and background radiance [6], was used to help quantify site factors that were examined.

Goldstone is at an elevation of 1040 m, much lower than any of the other potential California sites. Since it is in a desert area, vegetation is minimal. Precipitable water vapor measurements are not available for Goldstone. LOWTRAN7 calculations were done for all of the sites to predict both transmission and background sky radiance (Figs. 2–8). Maximum transmission at Goldstone was found to be 88 percent at zenith at 1.064 μm . The graphs indicate that the three other sites had a much higher transmission at all wavelengths and zenith angles. A tropospheric-haze model with 50-km visibility was used for the mountain locations, whereas a rural-haze model with 23-km visibility was used for the Goldstone calculations. These models were used because Goldstone lies in an area level with most of its surroundings, whereas the mountain sites will be above inversion layers that keep down the valley haze and increase visibility.

Daytime background sky radiance increases with increased particulate scattering. More scattering not only decreases signal transmission, but also increases background noise during the day. LOWTRAN7 calculations for radiance overall were highest at 0.532 μm and lowest at 1.064 μm , and radiance at Goldstone was approximately twice as high as that for the other sites. The coordinate system for radiance calculations is shown in Fig. 5. Figures 6–8 show the worst-case calculations, with the Sun at 30 deg from zenith (the highest it gets in the sky at that

¹ D. Wylie, personal communication, University of Wisconsin, Madison, Wisconsin, March 27, 1990.

latitude), and looking 30 deg from the Sun (the closest the AVM telescopes will be pointed to the Sun). Worst-case radiance in $W/(cm^2 \cdot sr \cdot \mu m)$ at $0.532 \mu m$ for Goldstone is 0.025, for TMO is 0.012, for Mount Wilson is 0.013, and for Mount Laguna is 0.013.

An experiment was done at TMO and Goldstone to test the performance of a charge-coupled device (CCD) camera and photometer when distinguishing stars from sky background during the day. The telescope was pointed at the star Altair, about 75 deg from the Sun, much farther than the worst-case calculations (30 deg). However, the differences in radiance could still be seen. Figure 9 is a graph of photometer readings of the background sky near Altair as it moved across the sky on the mornings of April 11 and 12, 1990. The differences in the number of photons collected are caused by the greater amount of background light at Goldstone. Increased haze resulting from the lower elevation and desert environment increase the amount of scattered sunlight, which in turn creates the background light. Readings for Goldstone averaged 517 counts higher than readings for TMO, a significant amount considering the total readings ranged from 1300 to 3000.

Goldstone's location on the desert floor inhibits detection of stars against their background because haze settles in valleys and on plains. Variations in transmission at all three wavelengths are shown in Fig. 10. The signal transmission is lower and daytime sky background noise is higher when compared with sites located above an inversion layer that confines the haze to lower altitudes.

TMO is at 2290 m, the highest of the California sites. Precipitable water vapor measurements indicate an average rainfall of from 2 to 8 mm annually [7]. The peak is covered with tall pine trees and low brush. It is above an inversion layer that confines valley smog, fog, and haze. LOWTRAN7 calculations indicate successful light transmission comparable to that of the other mountain sites, the maximum being 95 percent at zenith for $1.064 \mu m$. Figure 11 compares all three wavelengths, showing how transmission varies with wavelength and zenith angle.

Mount Wilson is at an elevation of 1740 m. Despite its proximity to Los Angeles, Mount Wilson does not have a significant problem with smog, since an inversion layer usually exists well below the summit. Cloud cover and coastal fog measurements taken for Los Angeles are not good indicators of conditions on Mount Wilson, since it is often above the low clouds and fog that cling to the coastline. The vegetation is similar to that at TMO. LOWTRAN7 light transmission and radiance calculations are similar to those for TMO. Precipitable water vapor measurements are not available.

Mount Laguna is at an elevation of 1860 m. Annual precipitable water vapor measurements average 5.2 mm [8]. LOWTRAN7 transmission calculations are similar to those for TMO and Mount Wilson.

Based on the above information, the following ratings were given to the sites for low particulate scattering: Goldstone: 4, TMO: 9, Mount Wilson: 8, and Mount Laguna: 9.

C. Suitability for a Future Large Optical Reception Station

The purpose of the AVM project is to enhance the cloud-cover model for optical communications from deep space to ground. Data will be collected from the AVM sites on atmospheric transmission and cloud cover. Should a site prove to be a favorable location for receiving communications from spacecraft, it will be a good candidate location for a receiving station. Current JPL projects include the design of a 10-meter segmented optical receiver [9]. Therefore, if data are to be taken on cloud-cover conditions at a specific site, it is desirable to choose one that can eventually accommodate a large receiver.

Goldstone is an excellent location for a large receiving station because it is already the site of the current U.S. node of the Deep Space Network (DSN) and can quite easily accommodate another receiver.

TMO is another JPL site that can accommodate a larger receiver. Dan Sidwell, the JPL site manager, has explained that the most desirable site on the mountain for a large receiver will be available in a few years should JPL decide to locate one at TMO. The large number of trees in the area would not significantly block observation because the view to the south, and hence of the ecliptic plane, is not obstructed. Difficulties in locating a larger receiver at TMO would arise from limited space available for buildings other than the AVM telescope itself. Lights from Mountain High, a nearby ski area, do not create problems for the AVM systems because the AVMs are designed to operate during the day. Any light creating difficulties for a large receiver can be filtered out since the ski area uses mercury vapor lamps that emit light at only a few narrow bands.

Mount Wilson has the advantage of being very close to JPL. In addition, it is not overcrowded with telescopes and has enough space for a large AVM facility. A disadvantage is that it is not already a JPL facility, as are Goldstone and TMO, so more negotiations would be involved in setting up a larger facility there.

Mount Laguna is currently operated by San Diego State University (SDSU) in the Cleveland National Forest. The ridge where the SDSU observatory is located still has abundant room for additional telescopes. But Mount Laguna often receives weekend visitors from nearby campgrounds because the observatory allows them to view the skies through a small antique telescope. There might be a conflict of interest in having a large number of people nearby when a large transmitter or receiver is being operated. Dr. R. Angione, director of Mount Laguna Observatory, does not foresee any problems with locating a large receiver there, however.

One problem common to all of the candidate sites is that of gaining approval from the Federal Aviation Administration (FAA) to restrict air space to transmit optical signals. This is because all of the sites are located near already restricted military air space (Goldstone), commercial air routes (TMO and Mount Wilson), or unrestricted space frequented by military and private aircraft (TMO and Mount Laguna). Transmitting at low angles to the horizon could result in laser penetration into these areas, which would interfere with air traffic. Solving this problem is beyond the scope of the AVM project, but air-space availability must be a factor in selecting a site for a large receiver.

Based on the above information, the following ratings were given to the sites for suitability of a future large optical reception station: Goldstone: 10, TMO: 9, Mount Wilson: 8, and Mount Laguna: 8.

D. Availability of Security and Maintenance

The availability of security and maintenance at a site are also considered because JPL personnel will not be able to frequently monitor the AVM observatory. Observatories must be protected from vandalism as well as accidents caused by curious hikers (therefore, it would be a good idea to put a fence around the AVM buildings, no matter where they are located). Minimal maintenance, such as snow removal and checks for weather damage or mechanical failure, is also necessary. It would also be useful to have someone available to call on in case a problem is detected from JPL. The designated individual could check the site and possibly close the roof until someone arrived to fix the problem. How often periodic checks would be required has not yet been determined.

Security at Goldstone is not a problem. Unauthorized personnel would not normally be near the observatory. But maintenance might be somewhat difficult because there is currently no one assigned to make routine

checks of facilities. Nonetheless, if the observatory is located near the Deep Space Station (DSS) 13 (Venus site), maintenance personnel will be close enough to add a routine visit to their daily tasks. A better site in terms of atmospheric conditions would be above the Apollo station, on a mesa about 200 feet higher than the surrounding area; however, maintenance personnel would be less available to make checks at that site.

TMO does not have the advantage of being restricted to JPL personnel. However, security has not been a significant problem there. The facility is staffed 24 hours a day, 7 days a week. Maintenance at TMO would be easily handled by the staff members who traverse the site every two hours on a fire-watch patrol.

Mount Wilson is not a very secure site since it quite frequently has visitors from the Los Angeles area. Therefore, a protective fence definitely would have to be erected around an AVM observatory. Another problem is that the only personnel who are available to make routine maintenance checks are observing technicians, who have many other duties. If a problem occurs, JPL personnel could drive to Mount Wilson since it is so close. However, this would take some time and would not be practical on a daily basis.

Mount Laguna Observatory is not secured from the rest of the National Forest by a fence. As mentioned before, campers are often present. Dr. Angione reported that only three minor events of vandalism have occurred in the past twenty years, none of which harmed any of the telescopes or other major equipment. Still if an AVM observatory is located at Mount Laguna, it would be a very good idea to have a secure fence around it for both safety and security reasons. The site superintendent could maintain the AVM observatory Monday through Friday when he is working. There would be no one on the site during weekends; however, the superintendent lives a mile from the observatory, so he might be available for emergencies.² Maintenance would be mostly limited to mechanical problems.

Based on the above information, the following ratings were assigned to the sites for availability of security and maintenance: Goldstone: 8, TMO: 9, Mount Wilson: 6, and Mount Laguna: 7.

E. Low Turbulence

Turbulence decreases the ability to obtain a focused image. Sites that exhibit low turbulence are usually at the

² R. Angione, personal communication, SDSU, San Diego, California, May 23, 1990.

top of a steep slope rising out of a valley in the direction of prevailing winds. Such sites also have no peaks in that direction higher than 1 km for at least 30 km. As with particulate scattering, the higher the elevation of the telescope, the better, because there is less atmosphere to blur images. Turbulence will be worse during daylight hours at any site due to the heat rising from the ground as it is warmed by the Sun. Turbulence is indicated by a site's capability of "seeing," a measurement of the blurring of an image.

Goldstone experiences greater turbulence than the other sites since it is at a low elevation in a desert, where the ground gets substantially warmer during the day, rather than at a high elevation with more vegetation. No good records of seeing have been kept at Goldstone since little optical work has been done there. However, a few amateur groups in the area have made some estimates of nighttime seeing. During the first part of the night, when the ground is cooling, seeing is generally poor, but it improves after midnight and then is generally between 2 and 10 arcsec. No measurements have been made during the day; however, seeing probably degrades greatly, due to the heat rising from the desert floor and the constancy of elevation in the area (if the site were 100 m or more above the surrounding desert, it would not be subject to some of the ground effects produced when looking at large zenith angles).

Seeing measurements have not been made regularly at TMO other than at its 24-inch telescope. There is some debate about how much of the seeing at this telescope is "dome-effect" seeing (light deflection thermally induced by air-temperature inhomogeneity in the observing path inside the dome). Measurements vary from 2 to 10 arcsec inside the 24-inch telescope dome. Some measurements were made using a 10-inch Celestron telescope both outside and inside the dome, to determine the variation in seeing. Measurements inside the dome were about three times worse than outside. This would indicate that seeing caused by the site, not the dome, is usually from less than 1 arcsec to 3 arcsec.

Seeing at TMO is not as good as at Mount Wilson because air does not flow to the mountain directly from the ocean. However, it is still good because the peak's elevation is above most ground features, and provides less atmosphere to blur images.

Mount Wilson exhibits the least turbulence. The laminar air flow from the ocean provides very nonturbulent conditions since no mountains obstruct it before it reaches Mount Wilson. Turbulent air occurs only when wind from the north crosses the San Gabriel mountains. Turbulence measurements indicate seeing to average 0.5 arcsec.

Mount Laguna does not have good records for average seeing measurements; however, Dr. Angione estimates that about 60 percent of all nights are photometric and that seeing is typically between 1 and 2 arcsec at those times. Occasionally, it has been better than 1 arcsec. The ridge on which the observatory stands runs north-south and is higher than any others to the west, so it exhibits laminar air flow from the ocean similar to that of Mount Wilson.³

Based on the above information, the following ratings were given to the sites for low turbulence: Goldstone: 6, TMO: 8, Mount Wilson: 10, and Mount Laguna: 8.

III. Rating

The ratings are summarized in Table 4.

IV. Conclusions

Table Mountain Observatory is the best location for the California AVM observatory. The excellent astronomical conditions at the site, combined with the convenience of its already being a JPL facility staffed full time and available for future use, make it the prime candidate for placement of the second observatory. The correlation of cloudy skies is also quite low between TMO and Mount Lemmon, Arizona.

No definite cost (lease, construction, maintenance, operations, etc.) information is available for any of the sites, therefore, cost was not a factor in this selection process. However, it seems reasonable to assume that locating a facility at TMO will be less costly than at a location where site rental fees would need to be paid, as at Mount Lemmon.

³ Ibid.

References

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Table 1. Major site factors

Factor	Percent
Low probability of cloud cover, fog, smog, and haze	30
Low particle scattering	20
Suitability of the site for a potential optical reception station	20
Low turbulence	15
Availability of security and maintenance	15
	100

Table 2. Annual clear-sky statistics

Factor	Candidate site		
	Goldstone	TMO/ Mt. Wilson	Mt. Laguna
Approximate annual sunshine [3], mean total hours	3600	3300	3400
Annual average daily direct normal solar radiation [4], MJ/m ²	24	20	21
Annual average daily opaque sky cover [4], tenths of sky	2.5	4	3.2

Table 3. Probability of clear skies, cirrus clouds, and opaque clouds

	January, percent			July, percent		
	Clear	Cirrus	Opaque	Clear	Cirrus	Opaque
Goldstone	49	20	31	67	13	20
TMO/Mt. Wilson	38	22	40	36	6	58
Mt. Laguna	33	21	46	46	9	45
Mt. Lemmon	39	23	38	26	33	42

Table 4. Rating the candidate sites

Factor	Weight, percent	Candidate site			
		Goldstone	TMO	Mt. Wilson	Mt. Laguna
Clear skies	30	10	9	9	6
Low scattering	20	4	9	8	9
Future suitability	20	10	9	8	8
Security and maintenance	15	8	9	6	7
Low turbulence	15	6	8	10	8
Total rating		7.9	8.85	8.30	7.45



Fig. 1. Sites investigated for locating atmospheric-visibility monitoring observatories.

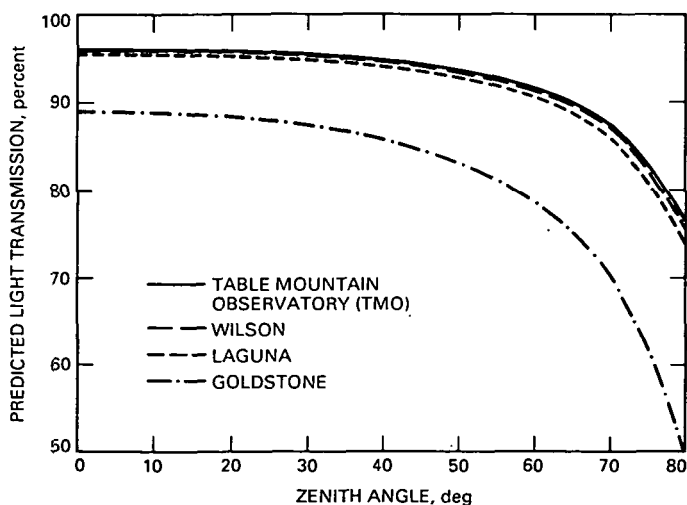


Fig. 2. Calculated light transmission at $1.064 \mu\text{m}$ for an average summer at candidate sites for atmospheric-visibility monitoring observatories.

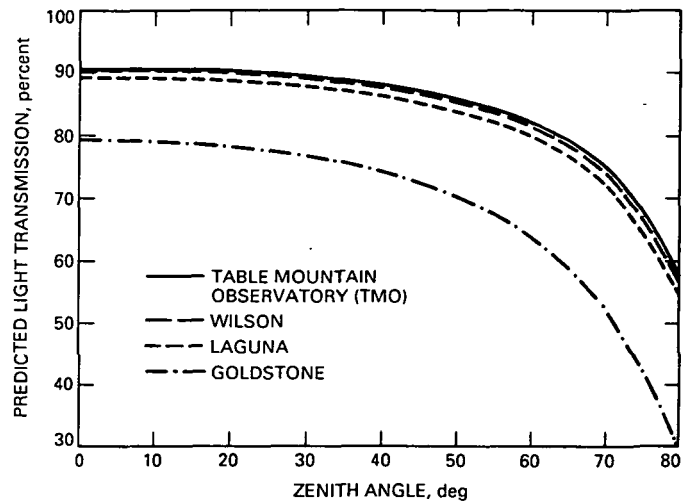


Fig. 3. Calculated light transmission at $0.830 \mu\text{m}$ for an average summer at candidate sites for atmospheric-visibility monitoring observatories.

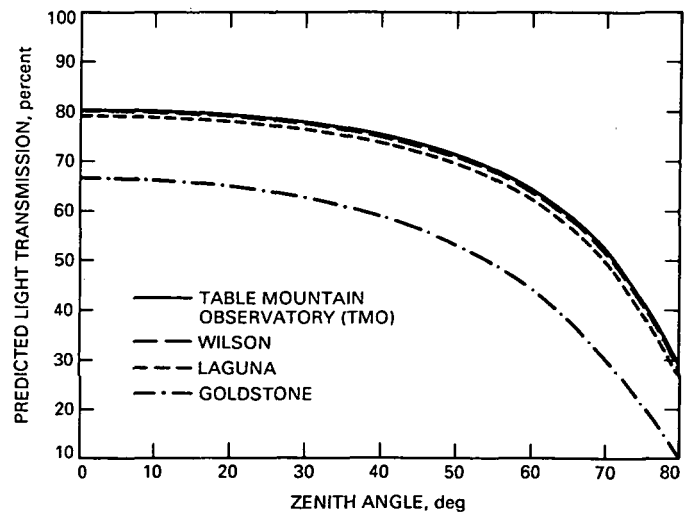


Fig. 4. Calculated light transmission at $0.532 \mu\text{m}$ for an average summer at candidate sites for atmospheric-visibility monitoring observatories.

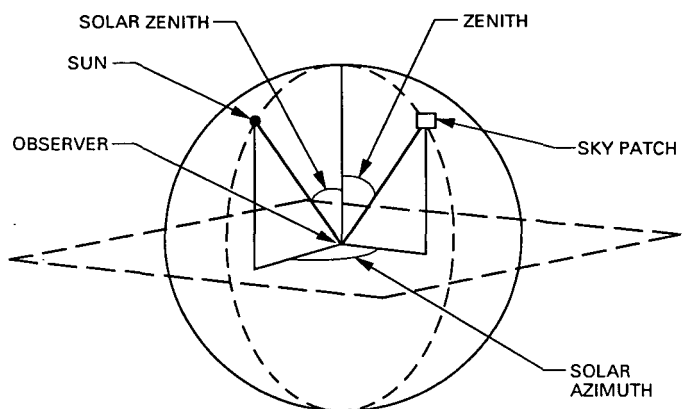


Fig. 5. Coordinate system for LOWTRAN7 radiance calculations.

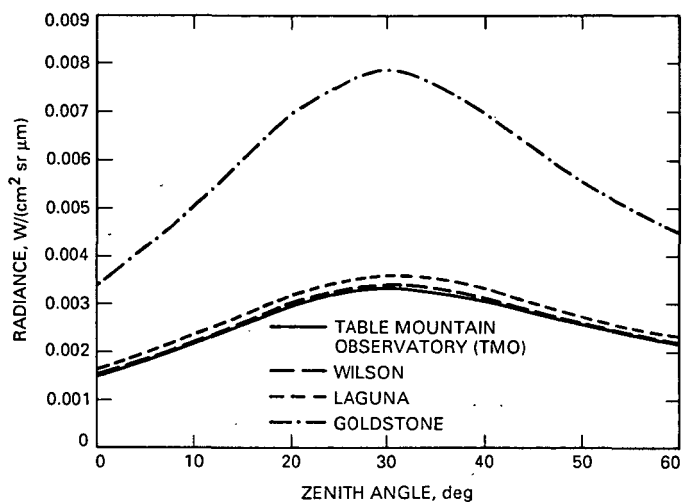


Fig. 7. Calculated radiance at $1.830 \mu\text{m}$, in the presence of cirrus clouds with solar azimuth at 30 deg and solar zenith at 30 deg, for an average summer at candidate sites for atmospheric-visibility monitoring observatories.

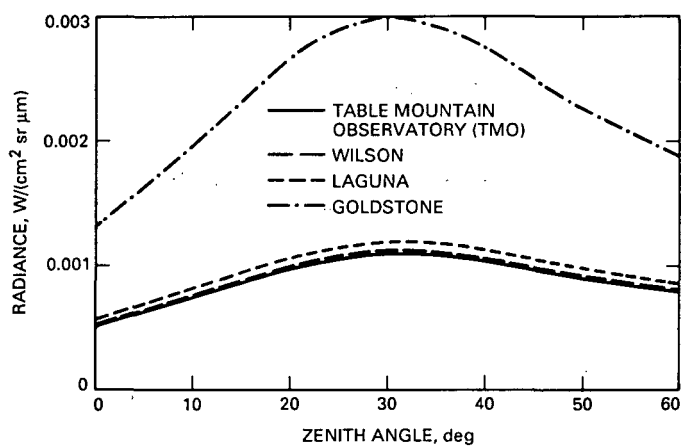


Fig. 6. Calculated radiance at $1.064 \mu\text{m}$, in the presence of cirrus clouds with solar azimuth at 30 deg and solar zenith at 30 deg, for an average summer at candidate sites for atmospheric-visibility monitoring observatories.

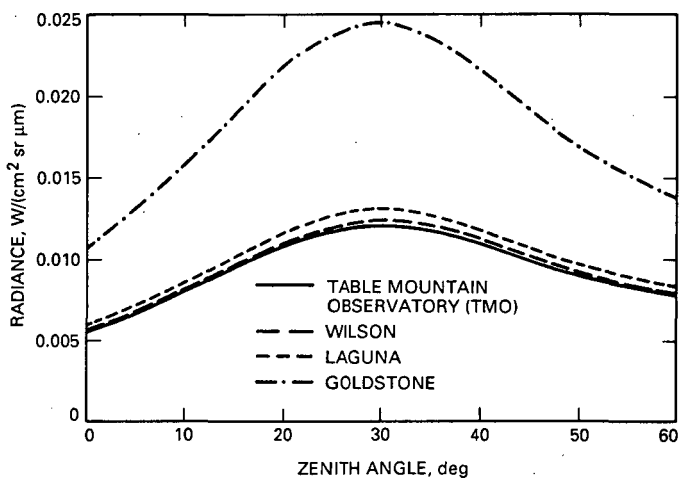


Fig. 8. Calculated radiance at $0.532 \mu\text{m}$, in the presence of cirrus clouds with solar azimuth at 30 deg and solar zenith at 30 deg, for an average summer at candidate sites for atmospheric-visibility monitoring observatories.

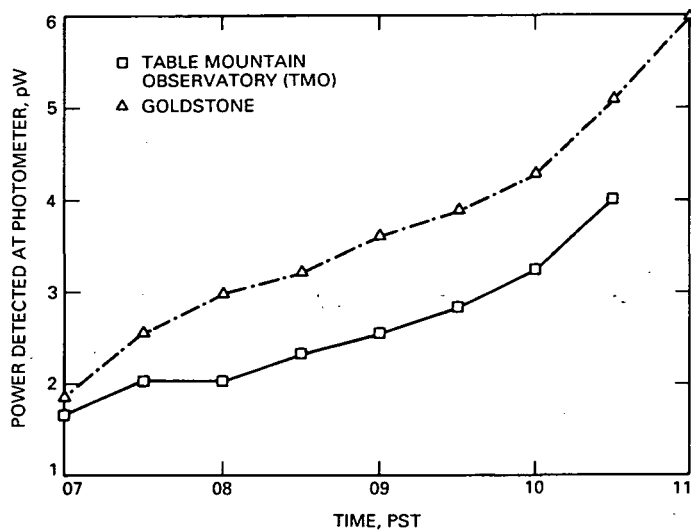


Fig. 9. Sky background photometer readings at $1.064\ \mu\text{m}$ for Goldstone and Table Mountain on April 12, 1990.

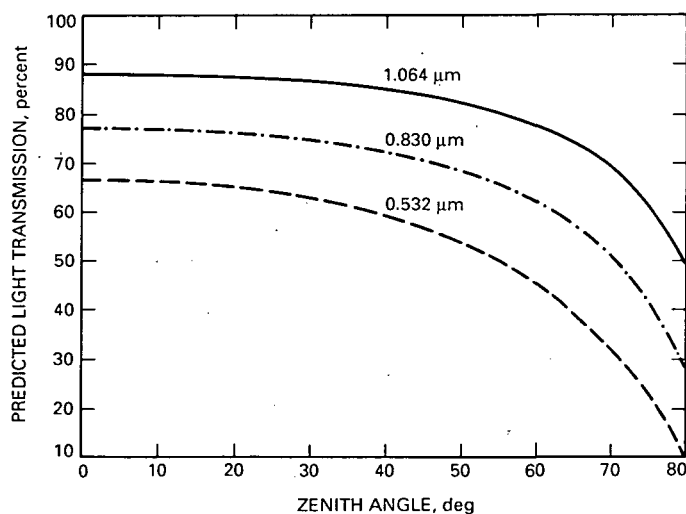


Fig. 10. Calculated light transmission at Goldstone for an average summer.

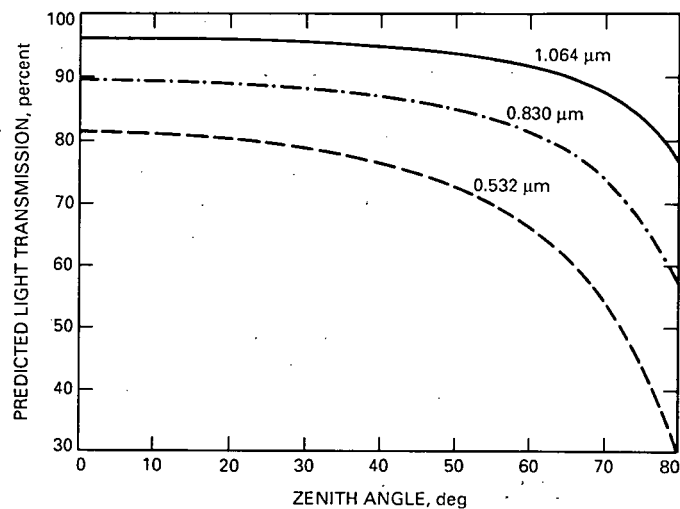


Fig. 11. Calculated light transmission at Table Mountain for an average summer.